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Analysis of end-of-life treatments of commercial refrigerating appliances: Bridging product and waste policies

Fulvio Ardente, Maria Calero Pastor, Fabrice Mathieux*, Laura Talens Peiró

European Commission, Joint Research Centre, Institute for Environment and Sustainability, Italy

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ABSTRACT

This paper analyses the relationships between product design and end-of-life treatment, but also between product and waste policies, based on a relevant case study. Commercial refrigerating appliance is a suitable case study due to its recent inclusions in the scope of two important European pieces of legislation, the Waste of Electric and Electronic Equipment Directive and the Ecodesign Directive. Commercial refrigerating appliances are business to business products with several peculiarities such as: customized design, high range of dimensions, content of complex electronic components and parts difficult to treat and recycle. The method used for the analysis: formalization, through literature review and survey of recycling plants, of treatments applied to the studied waste product; investigation of problems and difficulties in the recycling plants; identification of possible product-related improvement strategies; definition of workable product design options. For the analysis of actual recycling practices, data has been gathered through interviews with four European recyclers, and by consulting manufacturers and other experts of these products. Several potential design options to improve the recyclability of these products are identified and discussed, such as the design for dismantling of some key components, the restriction of some blowing agents and the labeling of insulation foams. The article finally shows how the enforcement of these design features, in particular through mandatory product policies such as the Ecodesign Directive, could facilitate their end-of-life treatment and hence ease the compliance with the waste legislation.

1. Introduction

Cooling and freezing appliances represent one of the most relevant categories of Waste of Electric and Electronic Equipment (WEEE). In terms of waste flow, they account for about 17.8% of total WEEE produced in the European Union (EU) (Huisman et al., 2008) and thus the corresponding environmental impacts. Research done in the past showed that most of the environmental impact of these appliances was due to the use of refrigerants as chlorofluorocarbon (CFCs) and hydrochlorofluorocarbons (HCFCs) (Molina, 1996). These substances have been identified as ozone-depleting substances by the Montreal Protocol on Substances that Deplete the Ozone Layer since 1987 (UNEP, 1987). In addition, the EU adopted the Regulation 2037/2000, which required Member States to remove those substances from all types of refrigeration equipment before any end-of-life (EoL) treatment (EU, 2000).

The evolution of refrigerators has increased their complexity in their composition, with the consequence of having products more difficult and less economically attractive to recycle (Allwood et al., 2011). Refrigerators can contain several other hazardous substances as: mercury (in switches and lamps), lead and cadmium (in batteries, capacitors and other electronic components). They contain also various valuable materials including base metals, plastics, scarce and precious metals.

As result of all these facts, various types of refrigerating appliances have entered within the scope of the waste legislation. Household cooling and freezing appliances (including refrigerators, freezers and air conditioning units) have been regulated by the WEEE Directive since 2002 (EU, 2002). Thanks to the enforcement of this policy, the recycling of household refrigerating appliance has been well established in the EU. Refrigerators, as Electrical and Electronic Equipment (EEE),[1] also fall within the scope of the "Restriction of Hazardous Substances" (RoHS) Directive regulating the content of various hazardous substances (EU, 2011).

* Corresponding author. Tel.: +39 0332 789238; fax: +39 0332 786645.
E-mail address: fabrice.mathieux@jrc.ec.europa.eu (F. Mathieux).

[1] Electrical and electronic equipment (EEE) means equipment which is dependent on electric currents or electromagnetic fields in order to work properly (Europena Union EU, 2012).

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Apart from vending machines, included in the "automatic dispenser" category, other product groups different from household refrigerating appliances were not clearly included in the WEEE Directive (EU, 2002). As noticed by Huisman et al. (2008) the reference to 'household' in the headings of some waste categories of the WEEE Directive indicates that 'non-household' appliances are excluded from the scope. As a consequence, the recycling of some categories of cooling appliances, as large Commercial Refrigerating Appliances (CRA),[2] has been developed differently by Member States of the EU. With the objective of harmonizing EoL treatments of WEEE across the EU, the recast of the WEEE Directive (EU, 2012) clearly stated that, starting from 15 August 2018, all the categories of EEE will fall within the scope of the Directive. This would include all the types of CRA as refrigerated display cabinets, beverage coolers and ice cream freezers.

1.1. Scope of the research

Changes in the waste policies such as the enlargement of the scope of the WEEE to new product groups, have generated in the past important impacts at various level additional burdens for local authorities, producers and recyclers (Huisman et al., 2006); additional costs for consumers (Gottberg et al., 2006); unexpected environmental and social impacts in developing countries due to waste shipment (Nnorom and Osibanjo, 2008); and increased traffic due to waste transport (Barba-Gutierrez et al., 2008). The enforcement of waste policies can be strengthened by synergies with other policies. The article 4 of the WEEE Directive encourages the "cooperation between producers and recyclers and measures to promote the design and production of EEE, notably in view of facilitating re-use, dismantling and recovery of WEEE, its components and materials" (EU, 2012). The application of strategies for ecodesign and, in particular, 'design for recycling', can allow the appropriateness of the future products with the EoL treatment processes (Ardente et al., 2003; Mathieux et al., 2008; Ardente et al., 2014). On such purpose, the European Ecodesign Directive (EU, 2009) represents a useful policy instrument to set some minimum requirements of the products, for example to exclude from the market products with insufficient recyclability performances. Meanwhile, considering that the enforcement of specific waste policies (as the WEEE and the RoHS Directives for the EEE) can also have the effect of encouraging innovation and product improvement among manufacturers (Mathieux et al., 2001; Lepochat et al., 2007), there is also a need to analyse the CRA product group with the aim to propose potential products' improvement for a more efficient recycling.

In this context, CRA is a good example on how its inclusion within the scope of the WEEE Directive could pose serious problems to recyclers in the near future. In fact, CRA not properly designed could hamper the compliance with minimum targets and requirements, as those set by the WEEE legislation.[3]

Even though many studies analyse the recyclability of household fridges and their treatment (see e.g. (Huisman et al., 2007; Deng et al., 2008; Sansotera et al., 2013)), little information is currently available about the EoL of CRA. In some cases, its EoL is assumed to be the same than for household appliances (BioIS, 2007). However, the structural and technical functionalities of CRA are considerably different from that of household cooling and freezing appliances. Among CRA there is a great disparity on design as they are frequently customized to specific needs of the clients in supermarkets or vending areas. Some of them have large dimensions (up to 7 m^2 of total display area and up to 10 m^3 of volume) and use some specific materials, as for example glass for the doors and large amount of insulation materials (up to 30 kg in large appliances). CRA can use remote refrigerating circuits, as for example the supermarket display cabinets. CRA can also contain specific components (e.g. electronics, controllers, lighting systems, locks, reinforced frames, anti-intrusion systems). Overall, the variability in the design and structure can cause some problems at the recycling plants, because recyclers are not aware about the product composition and cannot easily locate and extract certain components. Some CRA are also difficult to be collected, transported and handled due to their large dimensions at EoL. On the other hand, large dimensions can prevent this waste from uncontrolled disposal outside the regular collection channels, as largely occurring for small electronic appliances (Darby and Obara, 2005).

1.2. Aims of the article

This article aims to analyze the potential synergies between product and waste policies based on a relevant case study. Due to its recent inclusion in the scope of the WEEE Directive and in the work-plan of the Ecodesign Directive, CRA appears to be a suitable product group to analyze such synergies. In particular, the paper has the objective to analyse and better formalize the actual EoL of CRA in the EU, with particular focus to the pre-processing and recycling treatments in Europe. Another objective is to identify potential design improvements for CRA, based on a better knowledge of their EoL treatment. This paper is organized in eight sections. It starts with the description of the method for the analysis (Section 2). Then, it continues with a review of scientific and technical literature about EoL for CRA (Section 3), and a survey of actual recycling practices in the EU (Section 4). Section 5 analyses a number of criticalities of the CRA for their EoL treatments, based on the previously collected evidences. The article follows by discussing some products' improvement opportunities (in Section 6), and the discussion of the method and results (Section 7). Section 8 summarizes the main findings.

2. Method for the analysis

A detailed analysis has been performed to better understand the EoL processes for CRA in Europe and to identify current products criticalities, i.e. when the waste products are not fully adapted to recycling processes. The initial data collection has been carried out through three different data sources: literature review, survey of European recyclers and communications with experts.

The first source of the data collection consisted in developing an exhaustive literature review about CRA and other product groups with similar characteristics (e.g. household refrigeration appliances).

The second source was to conduct interviews and visits to several European recyclers. Four recycling plants, located in Italy, Germany and two in Spain, were contacted.[4] The selection of the plants was based on the discussion with a major European WEEE collection and recovery organization: this organization qualified these four recyclers as 'representative' for the EU geographical context in terms of treatments adopted for the processing of waste CRA. The questionnaire used during the interviews (see Box 1) included three sets of questions for the: (1) general understanding of the company and its representativeness in the national and European

[2] Commercial refrigerating appliances are here understood as the group of various refrigerating devices which store food and beverages for merchandising purposes.

[3] The WEEE Directive establishes obligation to treat certain components and the achievement of minimum recycling and recovery rates.

[4] According to communications from the recyclers, the four plants together treat yearly around 0.9×10^6 [kg] of waste CRA; moreover, the annual CRA flows in these plants range from 1% to 10% of their total WEEE input flows.

Box 1: Questionnaire for recyclers of CRA(inspired by Mathieux and Brissaud (2010).

Section 1: General question on the company

1.1. How is your company positioned in the local, national and European market? Do you have relationship with other companies/facilities in the EU?

1.2. What are the waste treated in the plant (type and amount)?

1.3. Can you describe the main processes implemented in the plant and, in particular, if and to what extent it is applied manual/automated extraction for depollution and/or re-use, shredding, sorting?

1.4. What technologies do you use in the plant for the recycling of waste?

1.5. Have you any management system (quality, environment, safety) implemented in your company? (if yes: Can you provide additional information on what data you monitor?)

Section 2: Treatments of CRA

2.1. Do you have any information about the CRA storage, collection, second-hand exports, main reuse/recycle/recovery routes?

2.2. What are the characteristics of the input end-of-life CRA treated in the plant (amount, age, type, dimensions, origin, and status of the waste at the reception)?

2.3. What is the age of the youngest end-of-life CRA that your plant treats?

2.4. Can you describe in detail each steps during the treatment of the end-of-life CRA (from the reception to the sorting of each fraction)?

2.5. What parts do you extract for de-pollution and/or reuse (if any)?

2.6. Is there any difference in the treatment of different type of end-of-life CRA (e.g. plug in refrigerators, remote refrigerators, vending machine)?

2.7. Can you describe the destination of recyclable fractions after their treatment in your plant?

2.8. What are the main difficulties observed in the treatment of end-of-life CRA?

Section 3: Future developments

3.1. Do you expect in the close future any changes in the treatment of end-of-life CRA (including changes in the amount of waste treated)? (if yes: what change? why?)

3.2. Do you have any suggestion regarding the design of the CRA to improve its recycling processes?

3.3. Do you have any suggestion for possible requirements for CRA to be enforced into policies?

market; (2) detailed analysis of the recycling treatments of CRA; (3) possible future development and improvement (at the company level, product level, or policy level).

Communications with experts (manufacturers of CRA, policy makers and members of an environmental agency) were the third source of information used (see questions 2.1, 2.8, 3.1, 3.2 and 3.3 of Box 1). This source of information was used to study possible analogies among the recycling of CRA and other WEEE, and to define possible solutions. Expert judgment was used when the previous ones were found insufficient or when contrasting evidences were detected. Mathieux and Brissaud (2010) showed that, when gaps concerning EoL processes exist in the literature and in statistics and no empirical data are available, expert judgements can be relevant to collect useful information.

Data gathered through the diverse sources were then structured and used: to analyze and formalize the chain of processes applied to the recycling of CRA; to detect the 'difficulties' encountered by recyclers when treating CRA; to analyze product's aspects that hinder the efficiency of EoL treatments; and to identify potential product improvements.

3. Literature review of end-of-life of refrigerating appliances

Scientific and technical literature can support the provision of information on EoL treatments, while statistics can provide information on the waste flows. However, no comprehensive analysis of EoL of CRA based on primary data from recycling plants (either on-site observations or interview data) has been found in the scientific literature.[5]

In 2007, the European Commission launched a preparatory study on Ecodesign of commercial refrigerators and freezers (BioIS, 2007). The study estimated that most of the CRA are renewed / refurbished and introduced in the second-hand market (and mainly exported to Africa, Asia, or Eastern Europe). Products not suitable for re-use are typically sold to scrap metal dealers, while a small fraction of the products (less than 1%, and mostly plug-in devices) is treated like household refrigerators in fridge recycling plants (BioIS, 2007). The only exception is represented by vending machines which, being already included within the scope of WEEE Directive since 2003, are assumed to be properly treated by recyclers (BioIS, 2007). However no additional detail on recycling of CRA is provided in this study. BioIS, 2007 also concluded that the treatment of ozone depleting substances is the only material efficiency aspect that could be addressed in the frame of the EcoDesign Directive, but without providing enough evidences to support this statement. This initial preparatory study has been recently updated with more focus on material efficiency aspects (Moons et al., 2014).

The average lifetime of CRA is around 8–10 years for CRA (BioIS,2007; DOE, 2009) compared to the average 14–15 years for household appliances (Laner and Rechberger, 2007; Deng et al., 2008; Ma et al., 2012; Sansotera et al., 2013). Appliances used in small groceries can have a much longer lifetime (DOE, 2009).

Information on waste flows of CRA in Europe is also very limited.[6] Eurostat data on WEEE for CRA is only available for automatic dispensers. The collection rate (by weights) of this WEEE category in 2012 was 31%, when compared to the amount of such products put in the European market in the same year (EUROSTAT, 2015). Such low collection rate might be partly explained by the combination of long time lag between the product is put in the market and its EoL and by the increasing amount of products put on the market. Other explanations for this low collection rate could also be assumed, including the importance of the second-hand market or the illegal shipments of waste. At the moment, these hypotheses can unfortunately not be verified in statistics.

Little information is also available concerning collection and transport of CRA at the end-of-life. These phases can be environmentally relevant for some life cycle impact categories (as particulate matter released during transport (BioIS, 2007)), as well as economically relevant.

Due to limited information about the EoL of CRA, the present literature review has been extended to household appliances. Recycling treatments of household appliances (household fridges, freezers and air conditioners) have been discussed by several authors (Kotera et al., 1999; Huisman et al., 2007; Laner and Rechberger, 2007; Deng et al., 2008; Ruan and Xu, 2011; CEN, 2012; Sansotera et al., 2013). These studies describe the EoL of household appliances as a combination of pre-processing, followed by

[5] Review performed in autumn 2013 and based on several scientific search engines (Scopus, Google Scholar, Science Direct, IEEE Explore).

[6] It is estimated that about 147×10^6 [kg] of waste CRA have been treated in the EU in 2012. The amount of waste vending machines has been derived from Eurostat statistic on waste "automatic dispenser" in 2012 (EUROSTAT, 2015). The amount of other waste CRA (plug-in and remote display cabinets) has been roughly estimated on the basis of the number and mass of devices sold (assuming an average lifetime of 8 years) (Bio Intelligence Services (BioIS), 2007; Moons et al., 2014).

shredding and mechanical sorting. The most difficult process during the recycling of household appliances is the proper extraction and treatment of refrigerants and insulating foams, which can both contain ozone depleting substances as CFCs and HCFCs (Kim et al., 2006; Huisman et al., 2007; Deng et al., 2008).

After the restrictions on the use of these substances set by the Montreal Protocol, hydrofluorocarbons (HFCs) have been progressively introduced as a substitute.[7] Although HFCs do not damage the ozone layer, they are gases with a very high Global Warming Potential (GWP). HFCs therefore require also their proper extraction and treatment (EU, 2012; Huisman et al., 2007). Policy restrictions and requirements on CFCs, HCFCs and HFCs also stimulated the use of some hydrocarbons as refrigerants (e.g. isobutane) and as blowing agents (e.g. cyclopentane) into foam insulation (GIZ, 2008). These hydrocarbons are characterized by low GWP but have a high flammability (Granryd, 2002). In order to reduce risks of fire or explosion during the recycling, special procedures and treatments have to be enforced in the recycling plant (CEN, 2012).

Recycling rates of household refrigerators have been also assessed by some authors. Kondo et al. (2001) estimated that the combined processing of disassembly and shredding of refrigerators has the highest recovery rate (more than 80% in weight). Ruan and Xu (2011) estimated that the recovery rate of refrigerators cabinet can reach 98% using of high efficient plants. Hall and Williams, (2007) observed the difficulty to recycle plastics in refrigerators due to their large variety and to their contaminations after shredding by fine metal pieces.

Some studies have also discussed some potential strategies to improve the EoL of refrigerators. The Centre for Remanufacturing and Reuse analyzed the remanufacturing of CRA in the UK and estimated that the increase of the remanufacturing of refrigerated display cabinets could prevent the generation of approximately 144,000 tonnes of CO_{2eq}/year, which is equivalent to the average annual emissions of nearly 50,000 cars (Walsh, 2009).

It is also recognized that an accurate 'design for disassembly' of refrigerating appliances, or some of their components, can contribute to improve the waste recycling (in terms of efficiency and of economic viability) and to reduce the impacts on resource depletion: this has been demonstrated by Shih et al. (2006) for CRA, by Jehng et al. (2002) for motors of CRA and by Seo et al. (2001) for household refrigerators. However these studies analysed the disassembly based on a mathematical modelling and do not include primary data concerning actual recycling practices and difficulties at the recycling plants.

In summary, the analysis of the literature shows that, due to their own characteristics, CRA deserve particular EoL treatments and their design present several improvement potentials. Little specific and quantitative information on the actual EoL treatment of CRA is currently available in the scientific and technical literature and in statistics. In order to cope with these gaps in scientific and technical literature, a survey of actual practices in European recycling plants has been performed, as detailed in the next section.

4. Survey of actual recycling practices in the EU

In order to enhance the design for recycling of equipment, several authors highlighted the necessity to have a deep understanding of the recovery treatments of waste, either by modelling processes steps (see e.g. van Schaik et al. (2002) and Mathieux et al. (2008)), or by collecting information at recycling plants (see e.g. Ardente and Mathieux (2014a)). Due to the lack of detailed information on the actual treatment (See Section 3), a collection of information at recycling plants was implemented in this study.

We surveyed four recycling plants that are specialized in the recycling of cooling appliances including CRA. The low share of CRA in the input flows can be related to the non-inclusion of CRA in the scope of the WEEE Directive[8] and hence to the limited flows of waste CRA reaching recycling facilities.[9] The findings of the survey relevant for the analysis are summarized in the next paragraphs.

Most of the appliances observed in these plants were at least 5 years old, but some were much older, in line with figures found in the literature review. Lifetime of CRA is a relevant parameter being that the old products have been possibly put in the market under different legislative requirements than today. For instance, refrigerators with mercury switches and CFCs are still reaching these recycling plants although these components are not anymore used since the enforcement of the RoHS Directive.

Once in the recycling plants, CRA are usually grouped into homogeneous batches with similar components and material composition (e.g. ice cream freezers from restaurants, refrigerators similar to households, vending machines, large display cabinets) to ease their handling and optimize the recycling processes.

The treatment of CRA differs from household refrigerators due to their large dimensions and the presence of some additional components (e.g. large glass parts, larger amount of electronic parts and lamps). Out of the four facilities, two of them treat internally the extracted refrigerants (incineration and/or preparation for recycling), while other two send these substances to external facilities for further treatments.

Based on the observation of the recycling plants, the EoL treatment of CRA can be formalized in 4 main steps, as depicted in Fig. 1: pre-processing, size reduction, shredding and mechanical sorting for recycling/recovery of various materials.

The pre-processing consists in the subsequent manual removing of some components and/or material for further treatments. The pre-processing has a key role in the recycling of WEEE since it allow to (Ardente et al., 2014): comply with current legislation on hazardous substances and waste; avoid potential contamination of other recyclable fractions during the recycling operations; facilitate, and in some case allow, the recovery of some valuable materials (including scarce and precious metals); avoid possible damage to the plant in the next steps. In general, refrigerant gases and oils are extracted from the refrigeration circuit by first piercing the circuits and then by suction. Both substances are collected separately and stored. For some types of CRA as large remote display cabinets, refrigerants and oils are extracted before the appliance is uninstalled. Compressors, shelves and electrical cables are also extracted at this stage. Components such as glass doors, electronic components (e.g. printed circuit board, capacitors, switches, thermostat, liquid crystal displays) and lighting systems (gas discharge lamps) are additionally dismantled when present.

CRA with large dimensions are successively cut in smaller pieces by manual and mechanical processing in order to be introduced into shredders. Vending machines usually need to be deprived of some hard parts (as iron reinforcements) before the shredding.

The third step includes the introduction of the waste through a series of shredders, which progressively reduce the CRA in small pieces (from 1 cm up to 10 cm). Blowing agents (such as CFCs, HCFs and hydrocarbons) contained in insulation foams are usually drained out during the first shredding step. Therefore, the initial shredding is done in a closed atmosphere to avoid emissions of

[7] HCFCs (especially HCFC-22) are still largely used in the refrigeration circuit and insulations of CRA in some countries (e.g. China) as observed by Fang et al. (2012).

[8] Before the recent recast, only vending machines were included in the scope of the Directive.

[9] It has been estimated that the waste CRA treated in the four plants amount to about 0.6% of the CRA yearly treated in the EU.

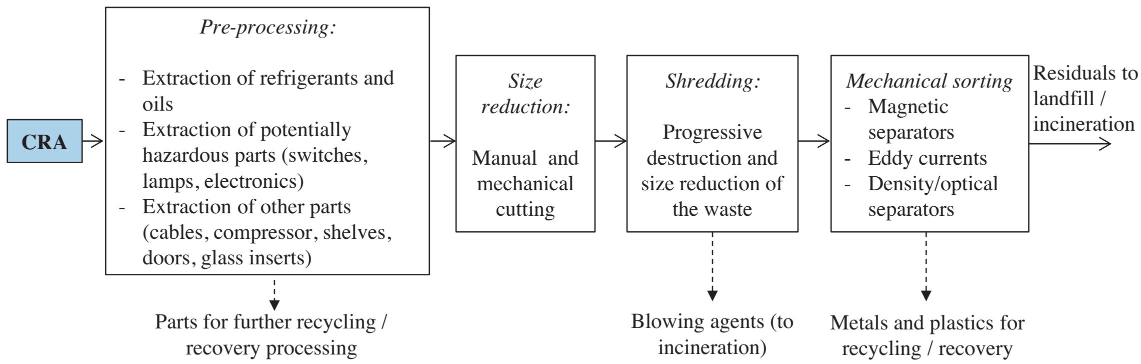

Fig. 1. Schematization of the treatment of commercial refrigerating appliances (CRA).

those gases into the environment. Nitrogen gas is injected in the chamber to reduce the risks of explosions when the concentration of these substances is excessive.

The automatic sorting of various materials is done by different technologies. The main valuable materials that are finally obtained include ferrous metals (sorted by magnetic separation), non-ferrous metals (copper, aluminium and zinc sorted by Eddy current separators), and some plastics (mainly PS and ABS sorted by density separators). These add up to the materials and parts sorted during the pre-processing. Non-recyclable materials such as PUR foams are usually incinerated with energy recovery or landfilled. However, two of the investigated plants convert PUR residues to pellets to be used in cement production.

5. Identification of criticalities of CRA

Criticalities in the products arise when the design of the products and waste treatment processes are not fully adapted among each other. Based on the results from the method, the following aspects have been identified for CRA: large dimensions of the appliances; presence of materials and parts difficult to treat as refrigerants and oils; insulation foams; and insulation blowing agents.

5.1. Large dimension of the appliances

The large dimensions and the composition of some CRA especially large display cabinets and vending machines can cause problems during the waste collection, transport and handling at the recycling plant. The transport and handling of large CRA can also cause safety problems for workers, environmental problems (e.g. due to the risk of accidental breakage of the refrigeration circuit during the transport and the release of polluting substances) and large costs. However, the analysis in the recycling facilities showed that large dimensions do not univocally represent a problem for all the recyclers. Detected difficulties are in fact related to the dimensions and capacity of shredders installed in the recycling plants and their loading system and capacity. Large dimension CRA represented a critical point in two of the recycling plants interviewed.

5.2. Presence of refrigerants and oils

The proper management of refrigerants and oils is very important during the recycling of refrigeration appliances. CRA have to be carefully manipulated during the EoL collection and handling to avoid leakages. When CRA reaches the recycling plant, refrigerants and oils are extracted and stored for further treatments. The extraction of these substances should be carefully performed in order to reduce the risks of accidental breakage of the refrigeration circuit and dispersion in the environment, in compliance also with environmental and safety legislation and standards. The extraction and recycling of alternative refrigerants, as carbon dioxide (CO_2) and ammonia (NH_3) could also cause some additional safety concerns because refrigerators with CO_2 work at high pressures, while NH_3 is a toxic substance. Overall, the extraction of conventional refrigerants was a critical aspect in all the four recycling plants visited, while problems for the extraction of the alternative refrigerants were observed only in one plant.

5.3. Presence of relevant parts difficult to be treated or containing valuable materials

The recycling of CRA needs also the processing of other potentially hazardous parts including various electrical and electronic components. According to the WEEE Directive (EU, 2012) the following components when present, should be separated from the other recyclable fractions: printed circuit boards (PCBs) larger than $10\,cm^2$; large electrolyte capacitors containing substances of concern; LCD larger than $100\,cm^2$; mercury containing switches or backlighting lamps; gas discharged lamps; batteries. These components can contain several precious and scarce metals, but also some critical raw materials: gold, silver, palladium, platinum (in PCB), indium (in LCD); rare earths (in fluorescent lamps and PCBs); and tantalum (in capacitors). They can also contain various hazardous substances such as mercury, arsenic, antimony, beryllium, cadmium and lead (EC, 2008).[10] If the components are not appropriately handled and extracted, all the materials and substances are dispersed in other recyclable fractions. Modern appliances are progressively adopting Light Emitting Diode (LED) lighting systems. Although the WEEE Directive does not provide specific guidance on the treatment of LED in EEE (EU, 2012), LED components could be problematic due to the potential content of hazardous substances, such as arsenic, lead gallium, indium, and antimony, which have the potential to cause human health and ecological toxicity effects (Lim et al., 2011). Furthermore, hard materials such as glass parts have to be preventively extracted to avoid potential damaging of the shredder's blades, especially in small and medium sized recycling facilities. The manual extraction of hard materials can however cause safety risks for workers. All four recycling sites raise as critical the handling of most of these parts contained in CRA. This was also confirmed by the review of the literature and the communications with experts. Glass handling was detected as a problem in two of the sites.

[10] Mercury is used in some lamps and certain electrical switches although progressively avoided in new products. The separation of PCB, switches, gas discharge lamps, capacitors, batteries and LCD is required by the WEEE Directive (2012/19/EU).

5.4. Presence of insulation foams

During the EoL recovery, the separation of insulation foams, especially polyurethane (PUR), is more difficult compared to other insulation materials (as e.g. polystyrene panels) (Zevenhoven, 2004). Foams insulation can produce fine dusts which contaminate other materials (e.g. metal fractions) and reduce their recyclability and value. The separation of insulation foams can occur before shredding (during the manual pre-processing) of after the shredding (with some density separators). This extraction of PUR foam was identified as critical based on the literature survey and the interview with one recycler.

5.5. Presence of insulation blowing agents

PUR foams generally contain some gases used as blowing agent which need to be separated and specifically treated (e.g. shredding into closed and controlled environments). These gases remain in the foam cells and contribute to the thermal performance of insulation (GIZ, 2008). Initially CFCs and HCFCs were used as blowing agent, however during the past decade these substances have been progressively substituted by HFCs, CO_2 and some hydrocarbons (GIZ, 2008). According to the UK Environmental Agency, 2012, fridge insulation foam containing hydrocarbon blowing agents should be classified as 'hazardous waste' because highly flammable. Due to such flammability, the shredding and sorting of foams is done in hermetically sealed chambers under controlled atmosphere (low oxygen atmosphere filled with inert nitrogen gas). However, a recycler pointed out the difficulty in optimising the treatment of blowing agents due to the lack of information concerning the type and amount of gas contained in the waste CRA.This treatment of blowing agent was judged as critical according to all the interviewed recyclers and communications with some experts.

6. Product-related strategies for the improvement of the recyclability of CRA

Criticalities of CRA can be reduced by ensuring that product design and recycling processes are adapted one to each other. This can be done through two possible options: by changing the processes or by changing the products.

In industrial engineering, it is usually recognised that it is easier and cheaper to change the products more than the manufacturing processes (Salomone, 1995). This consideration can be extended to EoL processes thus the present analysis only focuses on product-related strategies to improve their recyclability.

'Design for recycling' aims at improving the product to better fit the recycling processes. This is well documented in the literature, and usually follows some general strategies as: the reduction at the source of the amount of waste through the improvement of the product's durability (Lagerstedt and Luttrop, 2006; Ardente and Mathieux, 2014b); 'design for easy depollution' (Graedel and Allenby, 1996); 'design for re-use / repair / remanufacture' (Graedel and Allenby, 1996); 'design for dismantling' (Duflou et al., 2008); 'design for separation' after shredding (Froelich et al., 2007); 'design for energy recovery' (Lacoste et al., 2011). In addition to these general strategies, operational guidelines can be found in the literature. Such strategies can concern product parameters such as materials, fasteners and architecture (Mathieux et al., 2008), but also the provision of detailed information on the product by various stakeholders (e.g. users, recyclers), either through labelling or documentation.

Recent literature (Dalhammar et al., 2014) highlighted that CRA have a potential of improvement on EoL management through ecodesign measures which could bring significant resource efficiency benefits. A case study by DEFRA (2011) showed that, environmental impacts could be reduced significantly (up to about 18% for some impact categories) due to the redesigning of refrigeration display cabinets through considering EoL criteria.

Based on the criticalities identified in Section 5, and based on 'design for recycling' literature, the following paragraphs introduce and discuss possible product-related improvement strategies that could be applied to CRA through mandatory requirements in the Ecodesign Directive context. These improvement strategies have been discussed with four manufacturers of CRA to assess their potential technical feasibility, during several stakeholder meetings of the Ecodesign Directive formal consultation process and other bilateral interactions. Benefits and drawbacks of such strategies have also been evaluated.

6.1. Large dimension of the appliances

The transport, handling and recycling of large appliances could be facilitated by implementing some measures of 'design for dismantling' as the avoidance or reduction of welding of some thick metal parts, the use of standardized screws and other 'easy-to-disassembly' fastening systems. However, according to manufacturers, setting up a standardized solution for all CRA is difficult due to the large customisation of the products. Even some CRA such as vending machines and beverage coolers are designed to be sturdy and not easy to be dismantled in order to avoid vandalism and prevent potential damages by the improper use of the public. For these reasons no prescriptive improvement option is here formulated, while it is generally suggested to manufacturers to take this into account during the product design.

6.2. Presence of refrigerants and oils

The recycling of refrigerants and oils can be improved by reducing their amount, using substitutes, and by improving the systems for their extraction.

There are several evidences in the literature showing a trend in decreasing the use of refrigerant in cooling appliances (Nakano et al., 2007; EMERSON, 2010). However, several interviewed manufacturers observed that the amount of refrigerant can only be reduced to some limited extent as their mass strictly influence the energy efficiency of the appliances. Moreover, manufacturers already dose carefully the refrigerants to reduce production costs.

The standard EN 378-1 recommends some safety and environmental measures about the selection of the refrigerant fluids and the possible replacement for certain applications (CEN, 2008). Conventional refrigerants can be substituted by alternative refrigerants as carbon dioxide (CO_2) which has a lower GWP. However, the use of CO_2 as refrigerant requires a special installation to operate at pressures that can exceed 100 bars. Thus, its use can cause some additional safety problems during the extraction of the refrigerant in recycling sites.

Another option is to improve extraction systems by the installation of specific extraction systems/devices as extraction valves similar to those installed in air conditioning systems. However according to manufacturers, the installation of an additional valve could increase leakages during operation and hence negatively affect the energy efficiency of the CRA. This would apply especially for appliances designed to be hermetically sealed (as required by the EU Regulation 842/2006).

The reinforcement of some parts of the refrigeration circuit could contribute to reduce the risk of breakage of the refrigeration circuit and accidental leakage of refrigerants. However, as highlighted by recyclers, the breakage of the refrigeration circuit before the treatment in the recycling plant is generally related to improper handling of the waste. This cannot be simply avoided with a better design of the product but need a proper management of the whole waste treatment chain.

Considering all the drawbacks and limitations of these potential design options, no prescriptive recommendation concerning this criticality can here be formulated.

6.3. Presence of relevant parts difficult to be treated or containing valuable materials

Finding general measures for the 'design for dismantling' of CRA is difficult due to the great variety of design features requested by clients. There is also some design limiting factors, as some glass components (e.g. porthole) which are intentionally sealed to reduce heat dispersions. Furthermore, as previously highlighted, electronic parts in vending machines and beverages coolers are designed to hamper their easy extraction in order to avoid vandalism or robbery.

Still with all the limitation mentioned above, improving the accessibility and dismantlability of 'key' parts could contribute to facilitate the pre-processing of CRA before shredding. Possible ways to facilitate the this are the use of screws and snap fits, the grouping of certain parts in specific and superficial compartments and the provision of information about their location and disassembly. The easy dismantling of 'key' parts would also improve the reparability of the appliances, which contributes to durability, and also to increase the recovery yields of several valuable materials including precious and scarce metals contained in electronic components (Chancerel et al., 2009; Meskers et al., 2009).

Discussions with some pro-active manufacturers of CRA showed that such design for dismantling strategy was already implemented in some cases with limited additional costs, but not generalized. This strategy is therefore flagged as 'workable' and will be further discussed in Section 6.6.

6.4. Presence of insulation foams

The substitution of PUR foams by other insulation materials is advisable from a recyclability perspective. On the other hand, PUR foam can fill uniformly interspaces of the appliances better than other insulating materials which can grant a higher thermal insulation, hence contributing to a higher energy efficiency of the appliances. Considering this, and after discussion with manufacturers, a substitution of the PUR is judged as not technically feasible and no prescriptive design option is here formulated.

6.5. Presence of insulation blowing agents

Potential improvements on blowing agents include their substitution by less harmful substances, for example the substitution of HFCs with hydrocarbons or CO_2. The use of blowing agent is very relevant in terms of operating performances of CRA, being that blowing agents contribute to the structure of the insulation and consequently, to reduce heat losses and improve efficiency during operation (GIZ, 2008).

Another improvement strategy is based on the provision of information from the manufacturers to the recyclers as for example concerning the type and amount of agents used. As highlighted by one recycler, the preventive knowledge of such information (e.g. with an appropriate label on the product) would allow selecting the best treatment for the waste (e.g. treating together CRA with the same agents), reducing the risks of releases of the agent in the atmosphere and ignition/explosion (e.g. optimizing the amount of nitrogen in the shredding chambers). Although some manufacturers already implemented this labelling, it is far to be generalized and this could pose problems to recyclers.

Considering the current efforts of several pro-active manufacturers in the directions of substitution and of labelling, these two strategies are flagged as 'workable' and will be further discussed in Section 6.6.

6.6. Possible design options for the improvement of recyclability of CRA

The three most promising and workable design options to improve the recyclability of the appliances have been identified in the previous paragraphs: the 'Design for dismantling' of key components; the restriction of the use of HFCs as blowing agent in insulation foams; and the labelling of blowing agents used in insulation foams.

6.6.1. Design for dismantling

'Design for dismantling' strategies could be promoted for these components via several possible design options (Allwood et al., 2011): ease of identification, access, handling and separation. The 'ease of identification' can be ensured for instance by making the components directly visible to the recycling operator after removing the external covers or lids. If components to be extracted are not directly visible, appliances could be marked to facilitate their location (e.g. by placing in the back panel of the appliance, labels, sketches, drawings or pictures with the location of these components). The 'ease of access ' can be ensured for instance by designing the appliances so that the targeted components are accessible in few dismantling steps after removing the external covers or lids of the appliance. The 'ease of handling' can be achieved by minimising the number of different components, e.g. by using modular design and standardized parts. The 'ease of separation' can be granted by the design of components to be separated manually for instance with the use of appropriate screws and snap-fits as fastening systems (including innovative ones, as reported by Duflou et al. (2008)) and avoiding the use of glue or welded parts.

6.6.2. Restriction of the use of HFC as blowing agent in insulation foams

A potential design strategy could focus on the restriction of the use of these substances in insulation foams of CRA, hence reducing significantly some environmental impacts. For example, assuming a content of 10% in mass of pentafluoropropane (HFC 245fa) in PUR (GIZ, 2008), a mass of 4.175 kg of PUR foam in a vending machine (BioIS, 2007), and a GWP factor for HFC-245a of 950 [$kgCO_2eq/kg$] (Hauschild and Potting, 2005), we estimate that about 400 [$kgCO_2eq$] are caused by the blowing agent. The total GWP of a vending machine is estimated to be about 13,622 [$kgCO_2eq$] (BioIS, 2007), thus the substitution of HFCs in insulation foams can reduce by 3% the overall GWP. Restrictions in the use of HFCs as blowing agents are been progressively adopted by pro-active manufacturers. Moreover, they are under discussion in policy, as for example within the Regulation for fluorinated greenhouse gases (EU, 2014). Any potential restriction of the use of HFCs should however also consider the environmental impacts and other problems (e.g. related to flammability) of the potential substitutes (as CO_2 and some hydrocarbons) (GIZ, 2008). Manufacturers of CRA raised also their concern about the need to gradually shift from HFCs to other blowing agents in order to allow the implementation of the required technological changes.

6.6.3. Labelling of blowing agents in insulation foams

The provision of information about the type and amount of blowing agent through a label would facilitate recyclers the sorting of CRA before EoL treatments, thus optimising the dose of nitrogen in the shredders. This label would allow to implement appropriate safety procedures in the recycling plants of CRA and would also permit the monitoring by the surveillance authorities on the use of substances as blowing agents.

Some manufacturers state that the labelling of blowing agents is already done on a voluntary basis through the standard IEC 60,335 (IEC, 2012). The labels include the chemical name and principal component of the blowing agent, and a risk symbol on flammability as the one suggested by (ISO, 2011). However, the voluntary nature of this labelling scheme does not guarantee that the labelling will be present in the near future on all waste CRA reaching recycling plants. Moreover, considering the existence of this voluntary scheme, it is believed that a mandatory label of the blowing agent would not imply prohibitive extra burdens and costs on manufacturers.

7. Discussion

7.1. Bridging waste and product policies

The analysis presented in this paper aims at identifying better the potential synergies between product and waste policies based on a relevant case study. CRA has been identified as a suitable example of equipment due to its recent inclusion in both WEEE Directive and the Ecodesign Directive. The method that was used for the analysis can be summarized in the following steps: formalization (through literature review and survey of recycling plants) of treatments applied/applicable to the casestudy waste; investigation of problems and difficulties in the recycling plants; analysis of possible product-related improvement strategies including potential benefits and drawbacks; definition of workable product design options. These steps are summarized in Table 1.

The analysis performed on CRA provided knowledge and evidences that are useful both for the WEEE and for the Ecodesign Directives: for the WEEE Directive, the analysis brought relevant understanding concerning the fate of waste and the treatments applied to them; for the Ecodesign Directive, product criticalities and design improvement opportunities were identified. More importantly, this analysis has brought together some knowledge that are of common interest to both policies. In fact, the WEEE Directive states in article 4 on product design that 'Member States shall take appropriate measures so that the ecodesign requirements facilitating re-use and treatment of WEEE established in the framework of the [Ecodesign Directive] are applied'; while Annex I of the Ecodesign Directive states that 'possibilities for reuse, recycling and recovery of materials and/or of energy, taking into account the [WEEE Directive] must be assessed where relevant'.

The results of this analysis are particularly useful for product policies because the analysis of criticalities led to the identification of three workable design options to improve the recyclability of the CRA. These design options could be implemented in different ways. First of all, they could be voluntarily adopted by manufacturers in their design cycles. Three interviewed manufacturers judged these options as technically and economically viable and it is possible that several manufacturers could implement them in their design cycles in the short term. Alternatively, these design options could be promoted by mandatory minimum requirements in the context of the Ecodesign Directive. This would have the major advantage to generalise such minimum design rules to all CRA and hence to ensure that, in the near future, only CRAs with minimum recyclability performances reach the recycling facilities.

It should be noted that at the time of the submission of this article the design options identified in Section 6 were discussed for their potential adoption in the implementing regulation the Ecodesign Directive for CRA. This was carried out through an intense discussion, held in 2013 and 2014, between stakeholders (e.g. manufacturers, recyclers, NGOs) and policy makers (e.g. EU member states or European Commission) during the formal consultation process of the Ecodesign Directive. This demonstrates that the approach presented in the paper turns to be effective and successful for the case study of CRA: it should bring better alignment between product characteristics (defined in the context of the Ecodesign Directive) and recycling treatments (defined in the context of the WEEE Directive). Such consistent and synergetic alignment of waste and product policies is summarised by the 'virtuous' circle presented in Fig. 2: product requirements would enhance new models of products in the market with better characteristics from an EoL perspective, and allow, in the medium-term, an improvement of recycling treatments in terms of quantity and quality of recycled materials. New models of product would probably have new characteristics and require also a new analysis of EoL processes.

Setting up the 'virtuous' circle, as described by Fig. 2, is desirable and should be especially considered when new policies (both waste and product policies) are proposed or revised, or when waste and product policies are applied to new product groups.

7.2. Data gaps

The analysis of the EoL of CRA showed some data gaps. First of all there is little information available in the literature about impacts of the recycling of this waste. EoL is in fact sometimes neglected or not considered in environmental analysis of CRA. When it is considered, it is just assimilated to that of household appliances.

Data on the flows and fate of waste CRA are also lacking in EU statistics, except for automatic dispensers, mainly due to the former exclusion of CRA from the scope of the WEEE Directive. The analysis of the literature (Section 3) showed that the importance of the second-hand market and of the illegal shipments of waste of CRA is difficult to quantify. Indeed, although waste shipment has been regulated in EU (EC, 2006), illegal shipment of waste is still a phenomenon very difficult to control (EEA, 2009; Sthiannopkao and Wong, 2013). In the case of refrigerating appliances, illegal shipments seem to occur by declaring the waste as second hand appliances (SBC, 2011). Some countries started to block these activities such as Vietnam and Ghana that recently introduced a ban on the import of used refrigerators, including CRA among other appliances (BCCC, 2009; UNEP, 2013).

Thanks to the inclusion of CRA in the recast of the WEEE Directive, data gaps in statistics will probably decrease: data produced in the context of the WEEE Directive will hence be useful for the Ecodesign Directive. Detailed statistics especially about remanufacturing and second-hand market could allow a better understanding of all flows of CRA at their EoL.

7.3. Uncertainties of the analysis

All the reported data gaps surely bring some uncertainties to the analysis. The following paragraphs discusses other types of uncertainties.

In this article, primary data was obtained from interviews with European recyclers and manufacturers, and observations in recycling plants in central and southern Europe. Differences among the technologies installed in each recycling facility could partially influence the results of the analysis. For example, large shredders do not require the selective extraction of glass parts; difficulties due to large dimensions of the appliances can be reduced by automatic saws which facilitates the handling of waste along the plant.

In addition, the relatively long lifetime of CRA causes some uncertainties. In fact, CRA reaching now recycling plants are designed and manufactured at least 5 years ago. Therefore, current recycling treatments are focusing the attention on substances and components (as e.g. CFC/HCFC, mercury switches) not present any-

Table 1
Summary of the steps followed in the analysis of CRA for each stage of the recovery chain.

End-of-life step	Product's criticality	Rationale	Possible solutions	Potential benefits	Potential problems and drawback	Product design improvement
Collection, handling and shredding	Large dimensions	Problems during the transport and handling of large appliances	Design for dismantling of CRA	Simplification of EoL treatments with reduction of costs and safety risks	Possible conflicts with the customisation of the CRA Risk of vandalism and robbery.	–
Collection and pre-processing	Treatment of refrigerants and oils	Impacts due to the treatment of these substances (including accidental releases)	- Reduction of the use of refrigerants (dematerialisation). - Simplification of the extraction of refrigerant and oils - Strengthening and protection of the refrigeration circuit	- Reduced amount of refrigerants - Minor impacts and costs for the recycling - Reduced risk of accidental releases	The amount of refrigerant is generally dosed to optimize the energy efficiency. The installation of an extraction valve could cause leakages of refrigerant during operation. The design of heavy and sturdy products could make the pre-processing more difficult.	–
Pre-processing	Extraction of some components	Problems in the extraction and recycling of the components	Design for dismantling of: glass parts, lighting systems, electronic parts.	- Reduced labour costs. - Reduced risk of dispersion of hazardous substances (in electronics and gas discharge lamps). - Reduced safety risks for workers (in the case of glass). - Higher recovery yields for some relevant materials (in electronics).	Possible conflicts with the customisation of the CRA Some components are designed to be difficult to be dismantled for security reasons Lighting systems based on fluorescent lamps are expected to be progressively replaced by LED systems.	CRA shall be designed in order that, when present, the following electric and electronic components (printed circuit boards, electrolyte capacitors, LCD, mercury containing switches or backlighting lamps, gas discharged lamps, batteries) are easy to be identified, accessed and extracted for recycling.
Pre-processing and shredding	Treatment of insulating foams	Low recyclability of insulation foams	Use of more recyclable insulation materials	Increase recyclability of commercial refrigeration appliances with benefits in term of waste minimisation.	PUR foams provide a high thermal insulation	–
Shredding	Treatment of blowing agents	HFCs have a high GWP; hydrocarbons are flammable	- Avoid the use of HFC in insulation foams - Use of alternative blowing agents - Labelling of the blowing agent	- Reduction of GWP impact, - Optimisation of the recycling processes into the shredders - Reduction of the risks of flammability.	Impacts of the alternative blowing agents	Use of HFC in insulation foams shall be avoided Manufacturers shall mark the back panel of the appliances with the type of the blowing agent used in the insulation, and related the risk of fire

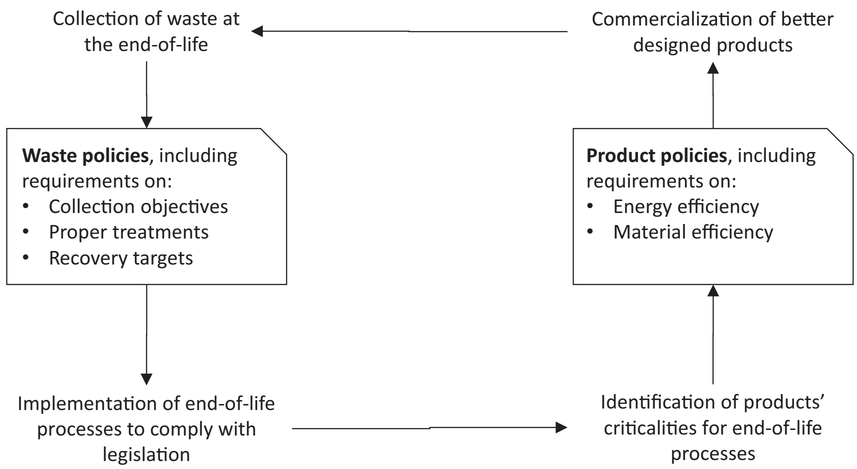

Fig. 2. A desirable 'virtuous' circle between waste and product policies.

more in new appliances. On the other hand, new problems could raise because of new components (e.g. LCD screen, electronics) recently massively installed in modern appliances, which have not reached their EoL yet. A continuous analysis of EoL treatments of CRA is therefore advisable in order to monitor the evolution of the sector and to provide information to manufacturers about actual recycling processes.

8. Conclusions

This article analyses the relationships among end-of-life treatments, product design and related policies, based on the analysis of a case study: commercial refrigerating appliances (CRA). This product group has been recently included into the scope of the WEEE Directive and in the workplan of the Ecodesign Directive and is hence a suitable case study for this analysis. The article offers a detailed and structured analysis of the current recovery processes of CRAs, based on available information in the literature, complemented with the survey of the actual practices at four European recycling plants and with communications with other experts (manufacturers, policy makers and members of a national environmental agency). Based on this analysis, the article also formalizes the treatments applied to the product group, and this was so far missing in the literature. Difficulties encountered during the EoLtreatment of CRA are then identified: large dimensions of the appliances, treatment of refrigerants and oils, extraction of some key parts (because difficult to be treated or containing valuable materials) and treatment of the insulation foams and blowing agents. Product criticalities are then spotted out and some possible solutions at the product design level are formulated and discussed;'design for dismantling' of some key components, restricted use of some blowing agents and provision of information with the labelling of the insulation foams. Such product solutions can be implemented by manufacturers either on a voluntary basis or through mandatory legislation. Implementation through mandatory policy instruments seem particularly promising to ensure that all waste CRA reaching the recycling plants present minimum recycling performances.

The article finally demonstrates the need to synergistically develop product and waste policies to ensure that product and process requirements defined in these pieces of regulation are consistent with each other, hence maximizing environmental and economic performances both for manufacturers and recyclers. A final discussion also highlights the data gaps and uncertainties faced during the analysis. Potential future improvements of the analysis are also presented: in particular, it is recognised the need to continuously update statistics and information about waste flows and available recycling technologies, since these are differently evolving in different countries especially after the inclusion of CRA in the WEEE recast.

Further research should focus on the application of the approach to other product groups and other policies (including e.g. voluntary policies on environmental labelling and green public procurements), to prove that the approach is sufficiently general to be transferable to other product contexts. Further research is also expected to support the formulation and verification of more stringent requirements concerning the EoL to be introduced into policies including strategies to support the verification by market surveillance authorities, through e.g. standardization.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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